Measuring Particulate Emissions from Green Ship Engines: State of the Art and Calibration Results

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Airborne Nanoparticles (WG: 3.43)

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BACKGROUND

Particle Emissions

- PM
  Particle Mass
  Per unit Volume
- PN
  Particle Number
  Per unit Volume
- BC
  Black Carbon Mass
  Per unit volume

Project Workflow

Literature Survey → Calibration/ Validation → Good Practice Guide

AGENDA

1. Regulation/Guidelines (IMO/ISO)
2. Literature Review: Expected Emissions
3. State of the Art (PN,PM, and BC)
4. Calibration Setup at PTB and Results
5. Key Takeaways and Further Steps

IMO REGULATIONS

MARPOL Annex VI (Reg. 14)

Regulating Particle Mass via Sulphur Limits

Area of Operation	Regulated Metric	Limit
Global Waters	Fuel oil Sulphur content SO_2(ppm)/CO_2(%v/v)	0.50% 21.7
Emission Control Areas	Fuel oil Sulphur content SO_2(ppm)/CO_2(%v/v)	0.10% 4.3

- Limits on amount of sulphur allowed in marine fuels.

MEPC.340(77):2021

- Ships using heavy fuel required to install exhaust gas cleaning system (scrubber).
- The ratio of SO_2 to CO_2 monitored continuously to prove the scrubber effectiveness.

MEPC.394(82): 2024

- Emerging focus on Black Carbon (BC) mass. Yearly BC measurements from exhaust emissions to be made while operating in or near the Arctic.

Measuremnent Guidelines

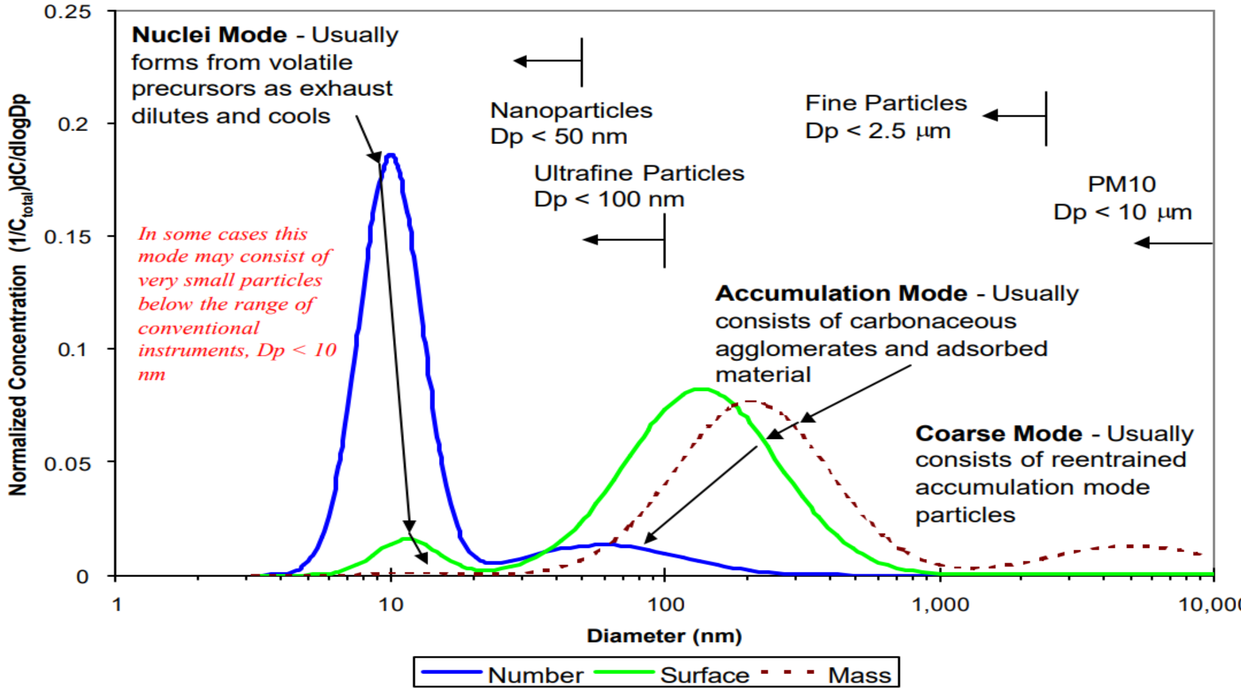
ISO 8178

https://www.iso.org/standard/79330.html

Kittelson, D.B., 1998.
https://doi.org/10.1016/S0021-8502(97)10037-4

Particle Mass Measurement: Suitable for Accumulation Mode, Blind to Ultrafine Particles (UFPs)

- Independent Researchers and manufactures follow ISO 8178, the global standard for exhaust emission measurement from non-road engines.
- Recommends measuring the particle mass by Gravimetric Method.
- Not suitable to quantifying emissions in ultrafine range (D< 100 nm), UFPs emerging air pollutant.



- Consequently , the EURO 6, and ISO 8178 (2020) introduced methods to measure PN down to 23 nm.
- In Euro 7, the threshold changed to 10 nm.

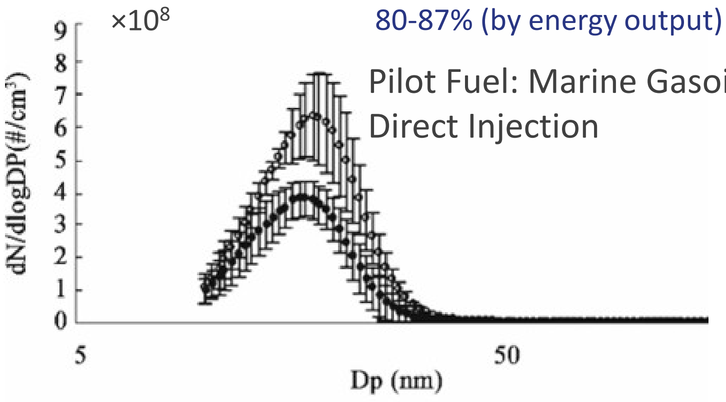
LITERATURE REVIEW

Fridell, E., Salberg, H. and Salo, K., 2021.
https://doi.org/10.1007/s11804-020-00150-6

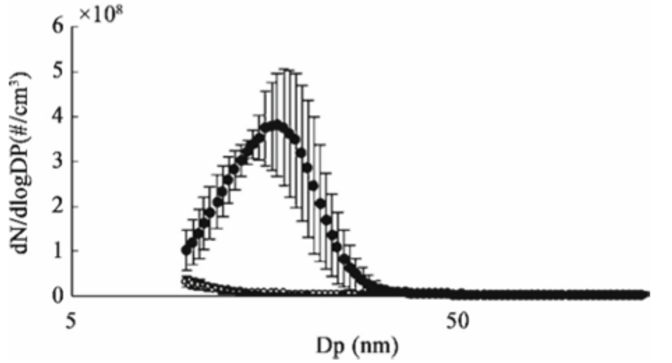
Green Fuel Emissions: From Particle Mass to Particle Number

MeOH share: 90-94% (by mass)
80-87% (by energy output)

Pilot Fuel: Marine Gasoil
Direct Injection



(a) Two different engine loads: 25 % engine load (open circles) and 80 % load (filled circles)



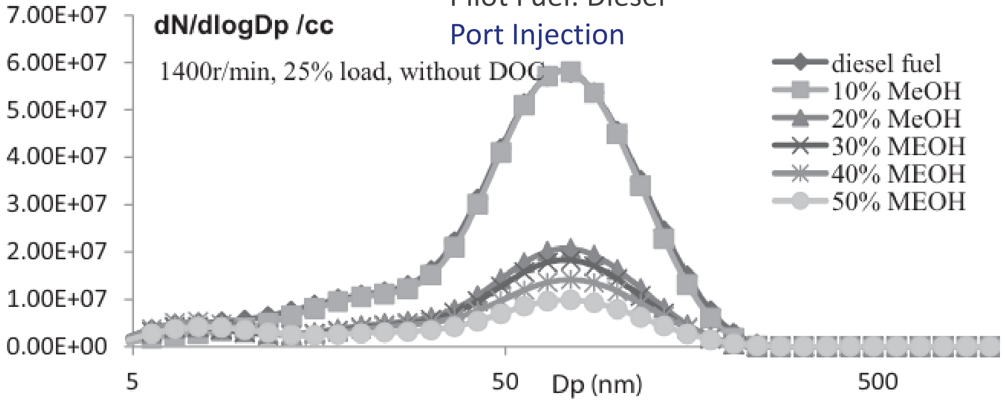
(b) 80% engine loads without thermodenuder (filled circles) and with thermodenuder (open circles)

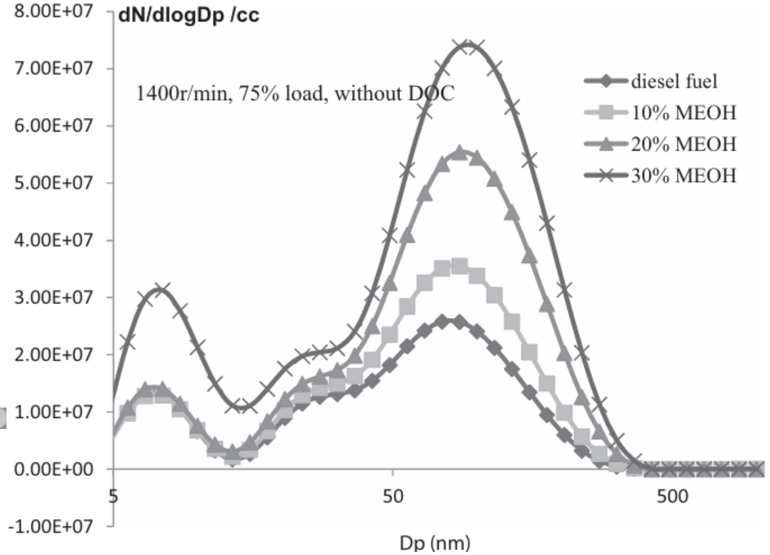
- Emissions are dominated by Nucleation mode, PN more critical than PM.

Geng, P., Yao, C., Wei, L., Liu, J., Wang, Q., Pan, W. and Wang, J., 2014..
https://doi.org/10.1016/j.fuel.2014.01.056

Blended Fuel Emissions: PM and PN

Pilot Fuel: Diesel
Port Injection





- Accumulation mode dominates at low engine loads. At high loads, emissions exhibits the bimodal distribution.
- The emissions not necessarily lower than the Heavy Oil Fuel e.g 75% engine load.

LITERATURE REVIEW

Fridell, E., Salberg, H., & Salo, K. (2021). https://doi.org/10.1007/s11804-020-00150-6
Momenimovahed, A., Gagné, S., Martens, P., Jakobi, G., Czech, H., Wichmann, V., Buchholz, B., Zimmermann, R., Behrends, B., & Thomson, K. A. (2021). https://doi.org/10.1080/02786826.2021.1967281
Zhou, J., Zhou, S., & Wang, Z. (2023). https://doi.org/10.1007/s11356-022-24594-1

Expected Emissions

Metric	Emissions Ranges
PN (Fridell et al., 2023,Geng et al., 2014)	10^4 – 10^8 particles per cm^3
PM (Zhou et al., 2023)	LSDF (4-Stroke): 10-20 mg m^{-3} HSDF (2 Stroke): 40-60 mg m^{-3} For blended fuel, data available in g/kWh or g/Kg
BC (Momenimovahed et al., 2021)	Diesel (4-Stroke at 10-90%): 1.2-10 mg m^{-3} DGMA (4-Stroke at 10-90%): 1-15 mg m^{-3} IFO (4-Stroke at 10-90%): 1- 40 mg m^{-3} For blended fuel, data available in g/kWh or g/Kg

Challenges

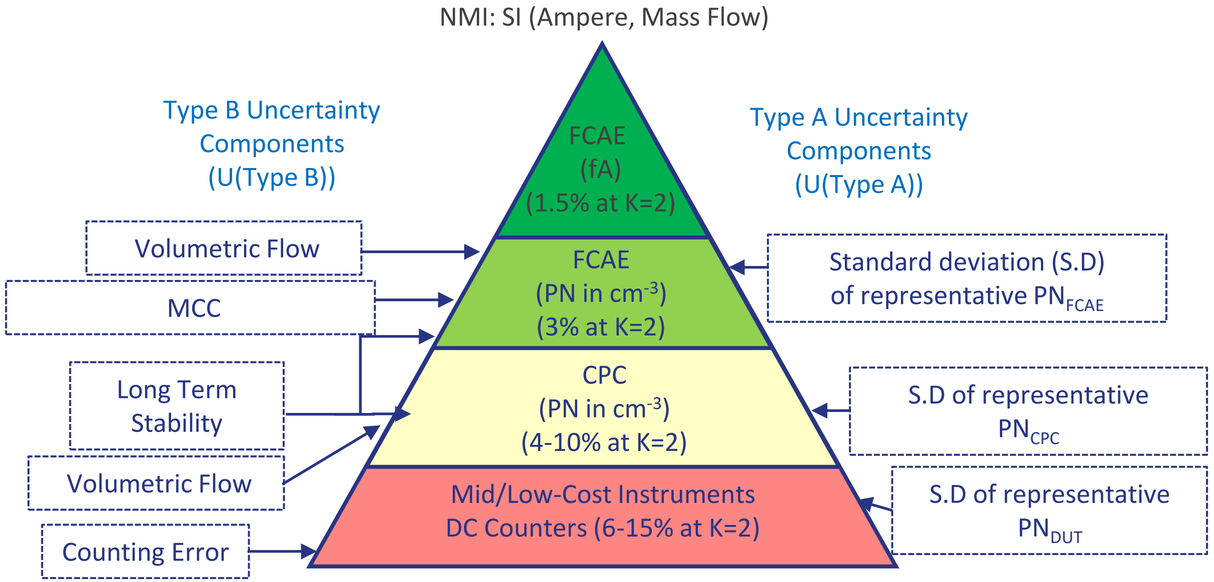
- **Unit Incompatibility**: Reported units (g/kWh, g/Kg, particle/kWh) different from conventional measurand of instruments (mg/m³, µg/m³, particle/cm³). Conversion requires real-time exhaust flow and engine power data.
- **Wide Emissions Range**: Depending on methanol content and engine load, emissions ranges vary massively in Particle Number (10^4 - 10^8 cm^{-3}) and Mass (µg to mg m^{-3}), straining instrument limits.
- **High Organics**: Volatile particles may cause measurement artifacts (condensation/coagulation) and risks damaging sensitive instruments.

Solutions

- **Test Campaigns**: Measure the expected emissions from the test engine exhaust (particles/cm³ and mg/m³).
- **Dilution Systems**: Use precise dilution factors to manage extreme emission ranges and accurately quantify uncertainty.
- **Exhaust Conditioning**: Implement catalytic strippers or thermodenuders to vaporize organics and accurately isolate solid particles.

STATE OF THE ART:PN

ISO 27891
EN 16976:2024

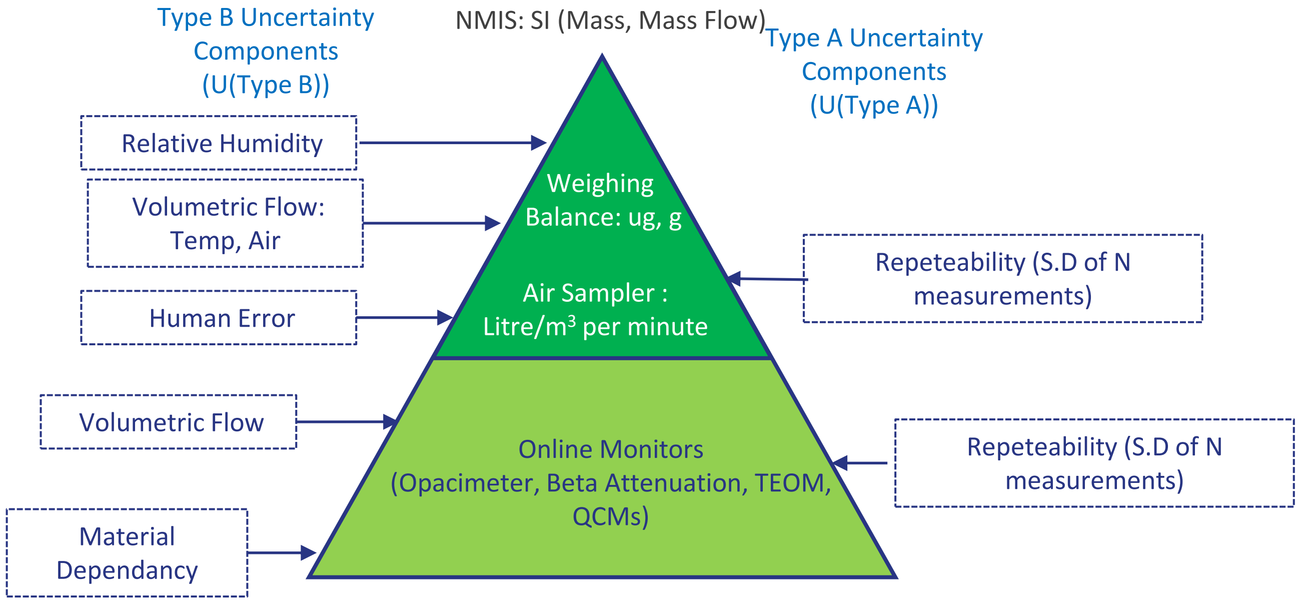


Measurement Techniques/Instruments	Measurement Range		Comments
	Size (nm)	Number (1/cm^3)	
Faraday Cup Aerosol Electrometer	2-1000	1-10^7	Reference Instrument for Metric PN Very High Cost, Suitable only for lab generated highly monodisperse aerosol
CPC/UCPC	2.5-1500	1- 10^5	High Accuracy: Transfer Standard High Cost
OPS/OPCs	300-3000	1- 10^4	Not Suitable for Particles Below 300 nm
APS	500-20 000	1-10^4	Not Suitable for Particles Below 500 nm
Diffusion Charging	10-10000	100- 10^8	Mid Cost PTI Sensor: Designed for raw, undiluted engine exhaust Moderate Accuracy.

STATE OF THE ART:PM

ISO 8178-1

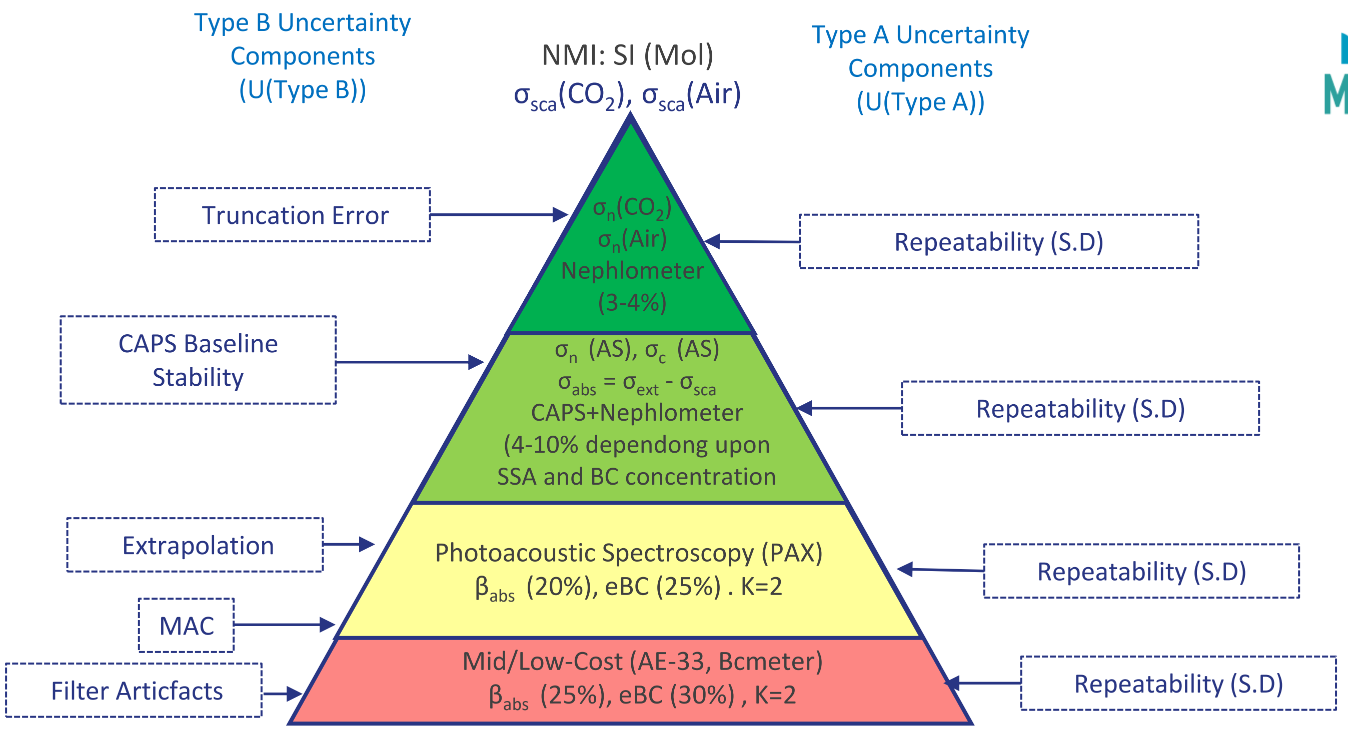
ISO 8178-9, ISO 11614
Euro IV and Euro V



Measurement Techniques/Instruments	Range (µg m^{-3})	Comments
Gravimetric Analysis	Dependent on filter size, sampling time, flowrate	Reference Method Offline method, labour intensive , delayed results, prone to human error
Opacimeter	0.3 mg m^{-3} - 800 mg m^{-3}	Moderate-Good Accuracy Low-Mid Cost
Beta Attenuation/Beta Gauge	1-10 mg m^{-3}	Good Accuracy High Cost, Suitable for ambient monitoring
Tapered Electronic Mass Balance	1-1000 mg m^{-3}	Good Accuracy Very High Cost, Sensitive, High Maintainenece
Quartz Crystlal Microbalance	0.1-150 ug m^{-3}	Suitable only for ultra-low mass environments such as controlled laboratory conditions and clean rooms.

STATE OF THE ART:BC

https://stanbc.com/outcomesimpact/

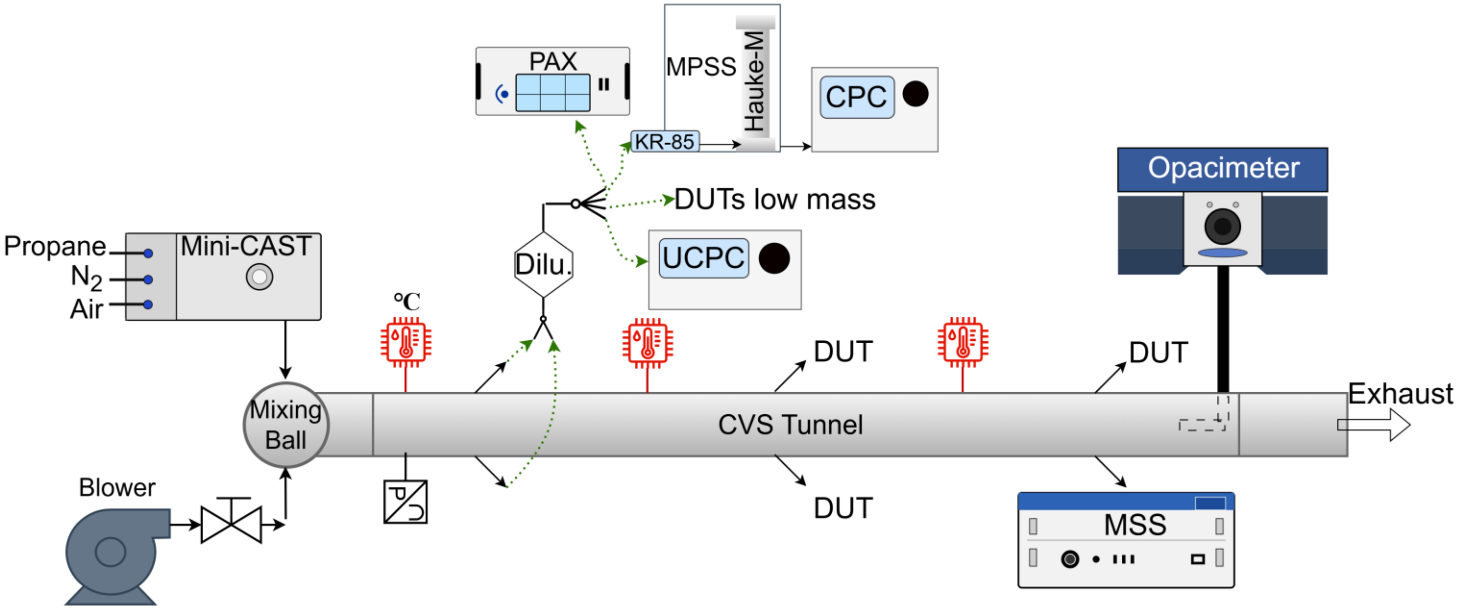


Measurement Techniques (Instruments)	Range (µg m^{-3})	Comments
Extinction Minus Scattering (CAPS + Nephelometer)	Dependent on Aerosol's σ_c	Reference Instrument for Metric σ_{sca}, σ_{ext} , σ_{abs} Very Costly, Very Low Portability
Photoacoustic Spectroscopy (PAX, MSS)	0.2 – 20 000 (PAX) 1 000-130 000 (MSS)	High Accuracy: Transfer Standard Costly , Low Portability
Filter – Based Photometers (AE, BcMeter)	0.1 -200	Low-High Cost, Moderate-High Accuracy
Thermal-Optical (EC/OC Analyser)	0.18 µg cm^{-2} of filter area	Costly, Offline Method: Labour intensive, delayed results, prone to human errors
LII (SP2)	1-12 500 particle/ cm^{3}	High Accuracy, High Cost, Low Portability, Blind to UFPs

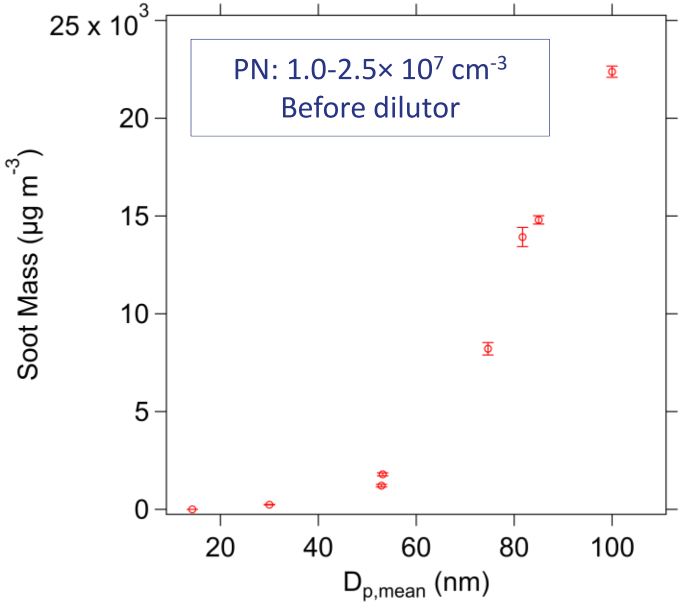
Petzold, A., Onasch, T., Kebabian, P., & Freedman, A. (2013). *Atmospheric Measurement Techniques*.
https://doi.org/10.5194/amt-6-1141-2013

CALIBRATION SETUP

Multi-Metric Aerosol Calibration Setup at PTB



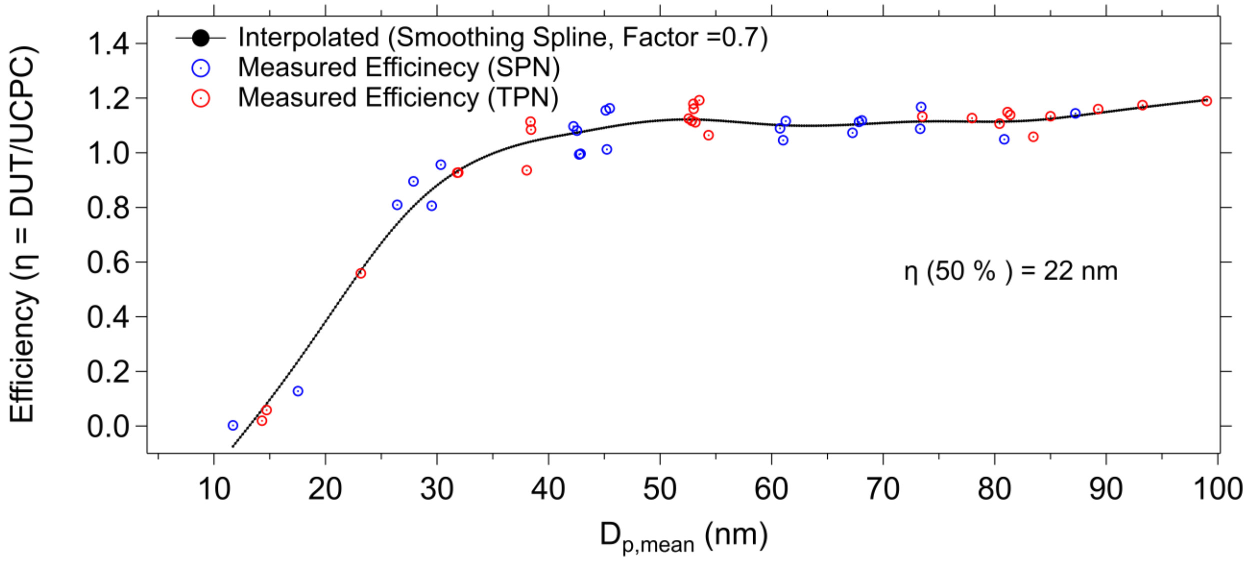
Reference Device	Metric (Range)
UCPC	PN (D_{50}: 2.5 nm, up to 3× 10^5 particles cm^{-3})
MSS	BC mass concentration (1–150 mg m^{-3})
PAX	BC mass concentration (0.2-20 000 µg m^{-3})
Opacimeter	Opacity (0-100% corresponds to PM mass: 0.3-1000 mg m^{-3})



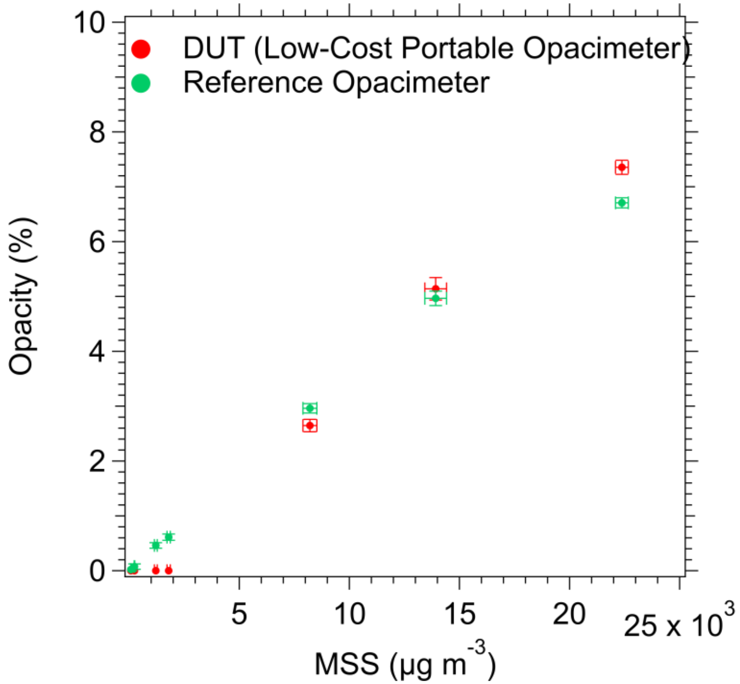
CALIBRATION RESULTS

Low/Mid-Cost Sensors vs. Transfer Standards

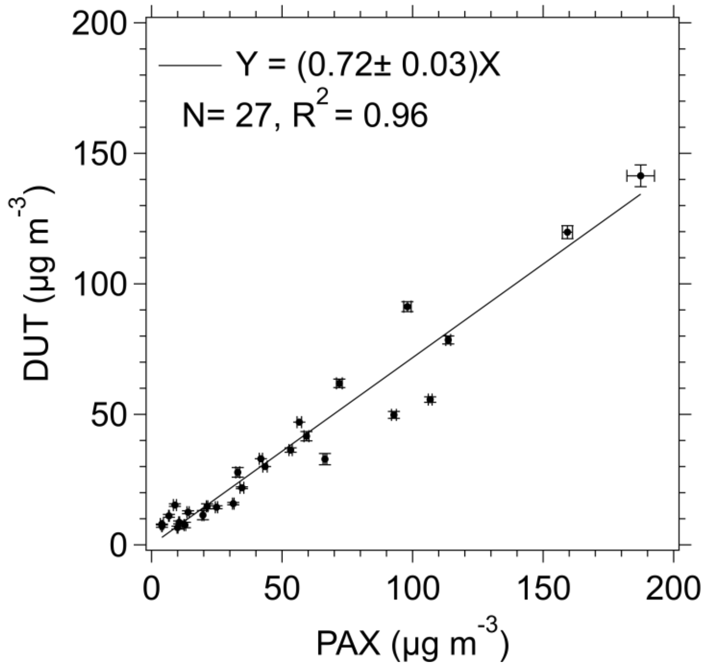
(A) PN: DC Particle Counter



(B) PM: Low-cost opacimeter



(C) BC: Low-cost filter based photometer



CALIBRATION RESULTS

Conclusions

(A) PN: DC Particle Counter

- Low efficiency below 30 nm ,may not be suitable for clean fuel emissions.
- A higher grade instrument (Engine Exhaust, EU 7, Dp_{50} at 10 nm) may be needed to measure particles down to 10 nm.

(B) PM: Low-cost opacimeter

- Good linearity with reference opacimeter and MSS in high mass range (> 5 mg m^{-3}).
- Good solution for Indicative/threshold monitoring. A higher grade instruments (Reference Opacimeter/MSS) may be needed for measuring low mass emissions .

(C) BC: Low-cost filter based photometer

- Strong correlation with PAX (10-200 ug m^{-3}). Performance (slope) can be improved further by optimizing the calibration parameter (C_0).
- High mass measurements can be done by employing well characterized dilutor.

TAKE HOME MESSAGES

Regulations & Standardization

- As we transition to green fuels, existing regulation and standardization may evolve for particle emission measurements.
- IMO is actively increasing its efforts to standardize the measurement of BC mass.
- In line with evolving standards (Euro7, ISO 8178), the IMO regulations should/may also extend to PN , a comparatively better metric to quantify the UFPs emissions.

Literature Gap on Emission Ranges: Prerequisites for Standardisation

- Knowledge about the expected emission ranges/composition necessary to set realistic limits and standardise the measurement protocols.
- Existing literature lacks usable data on the emissions ranges from the green/blended fuels.

Bridging Gaps through Metrological Solutions

- Test campaigns planned to map emissions (expected range, non-volatile content) from test engines (MeOH-Diesel blends) in MaritimeMET .
- A good practice guide for traceable measurement of PM, BC, and PN emissions from green ship engines.

Visit our website for more information
https://www.MaritimeMET.eu
Follow us on Linkedin for project updates
https://www.linkedin.com/showcase/maritimemet-project/about/

Kiitos.

Tak skal du have

Děkuju. Danke.

Merci ! Thank you.

Tack så mycket

Hartelijk dank.

Teşekkür ederim.

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EURAMET

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Visit our website for more information
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Discussions

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MaritimeMET

Metrology for Green Maritime Shipping:
Emission control through traceable measurements and machine learning approaches

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